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SUMMARY

We have grown AlGaAs/GaAs heterojunction bipolar transistors (HBTs) on InP. These AlGaAs/GaAs HBTs have been successfully fabricated on InP by incorporating InGaAs/GaAs strained layer superlattice in the buffer structure. Current gain from these HBTs on InP (about 30) is found to be generally smaller that that from AlGaAs/GaAs HBT on GaAs. PL studies of the GaAs buffer layer of a field-effect transistor layer on InP indicates that, of the five observable peaks, the excitonic transition at 1.513 eV has been identified with the help of optical reflection, absorption, and temperature dependent PL measurements.

The optical absorption spectra of coupled asymmetric quantum wells have been studied to assess their possible use as optical modulators. Optical transmission measurements on a series of structures consisting of GaAs well coupled to an InGaAs well indicates the possibility of achieving quenching of exciton signal at a relatively low bias.

Theoretical investigations have been carried out of the I-V characteristics of ion-implanted long-channel and short-channel photo-MESFETs. While gradual channel approximation has been used to model and analyze the long-channel MESFETs, the saturation of electron velocity due to high electric field has been taken into consideration in modeling and analyzing the characteristics of short-channel MESFETs. The distribution of electrons due to optical illumination has been assumed to follow an exponential function. The distribution of same electrons due to ionization of impurity atoms has, however, been assumed to follow a Gaussian profile. Optimization of both photon flux as well as wavelength was found to influence the I-V characteristics of the MESFETs. The theoretical analysis indicates that in order to obtain best optical response of MESFETs, the light must be incident on the gate region, and that the photon generated free carriers behave in the same way as impurity generated free carriers.

A great deal of effort has been put to establish our new multi-million dollar facility for gas-source molecular beam epitaxy. This will be an integral part of our research facility for optoelectronics research during the years to come. Almost all the necessary components have

already been obtained, and a significant progress has been made in testing and optimizing the operation of the machine.

We are in the process of growing various multi quantum well laser structures on InP and on other III-V semiconductors. We are planning to use this facility to grow and investigate various important optoelectronic devices, including feed-back lasers for high-speed direct modulation, p-i-n photodiodes, photoconductive detectors, and multi quantum well optical waveguides. Specifics are given in the following section.

We have recently undertaken a project of theoretical and experimental studies of heterojunction bipolar phototransistors (HPTs). Theoretical models are being developed with different structures and anticipated properties. Parallel experimental studies are also underway to examine the technological feasibility of the I-V characteristics and related properties of various theoretically designed HPTs.

SECTION II. PROGRESS MADE

A. GaAs on InP

Recently, there has been increasing interest in the growth of GaAs on InP as a means of combining the advantages of the well-established GaAs electronic device technology with long wavelength (1.3 and 1.55 μm) InP-based optical device technology on a single chip for low cost, high performance optical fiber communication systems. As part of our on-going research on the MBE growth of III-V semiconductors on III-V semiconductors, we have grown AlGaAs/GaAs heterojunction bipolar transistors (HBTs) on InP. Considering their superior high-current handing capability, currently we are studying the usefulness of these HBTs for laser drives for optoelectronic monolithic integrated circuits (OEICs). Since essentially as minority-carrier devices, bipolar transistors are very sensitive to defects, we are also trying to use this sensitivity property of HBTs to test the material quality of the relatively new heteroepitaxial system thus obtained.

AlGaAs/GaAs single heterojunction bipolar transistors have been successfully fabricated on InP substrates by incorporating InGaAs/GaAs strained-layer superlattice in the buffer structure to reduce dislocation propagation to the epilayer [1]. Current gains of devices with 0.12 μm-thick base doped with Be to 1×10^{19} and 1×10^{18} cm^{-3} and with emitter area of $50 \times 50-$ μm^2 were 20 and 30 on InP as compared to 60 and 150 respectively for those on GaAs corresponding to a collector current density of 2×10^3 A-cm^{-2}. Current density as high as 1×10^4 A-cm^{-2} were obtained from these devices without degradation. The ideality factors of the emitter-base junctions were 1.3 and 1.2 for devices on InP and GaAs respectively. Since the minority-carrier lifetime is quite sensitive to defects in the base region, these measurements demonstrate the high quality of GaAs on InP.

In addition, attempts have been made to characterize low-temperature (4K) PL of the GaAs buffer layer of a field-effect transistor structure grown on InP substrate [2]. Of the five observable peaks, the excitonic transition at 1.513 eV, which is due to the impurity associated recombination at energy 1.483 eV, has been identified with the aid of reflection, absorption, and temperature and excitation-intensity dependent PL measurements. It has been noted that the peak at energy 1.504 eV, most probably due to an exciton bound to a defect, is greatly enhanced compared to that of homoepitaxial GaAs. The optical results strongly demonstrate that good quality GaAs films can be grown on InP substrates. The demonstration is consistent with the electrical characteristics of devices fabricated from the same sample [3].

B. Asymmetric coupled quantum wells

The optical absorption spectra of coupled asymmetric quantum wells have been investigated in order to assess their possible use as optical modulators. Three structures consist of pairs of quantum wells with varying well widths, separated by a thin barrier. Previous works on these types of structures reveal richer features and more dramatic changes in the optical transmission spectra when an electric field is applied.

In an effort to achieve higher modulation ratio, optical transmission measurements have been carried out on a series of structures consisting of a GaAs well coupled to an InGaAs well. From these measurements it has been noted that the quenching of the exciton signal originating from the GaAs well can be readily achieved at a relatively low bias (e.g., 3 V, 4.5 kV/cm). However, the exciton signal from the InGaAs well is found to show little change under an applied bias. The photocurrent measurements performed suggest higher modulation at InGaAs QW wavelength which contradicted the transmission measurements. When measurements were done at low temperatures (about 4 K) the quantum confined Stark effects became readily visible. These Stark effects were no more visible when the measurements were repeated at room temperatures.

In order to gain a better understanding of the processes involved in coupled quantum well (CQW) structures, optical transmission measurements have also been carried out on a series of GaAs coupled quantum wells. For these measurements, the length of the AlGaAs coupling barrier was varied from 20 Åto 40 Å, keeping other parameters constant. This was done in an effort to determine how the barrier length affects the coupling and energy levels of the coupled wells. We are planning, for very near future, to perform electro absorption measurements on the system, so that we can determine the role of the barrier width on the optical modulation ratio, and on the bias voltage needed to achieve such ratio.

Considering the complexity of CQW structures, we are presently trying to carry out a systematic study on the system. It will, hopefully, uncover the physics and technological importance of the effect of various parameters, such as quantum well width, barrier width, and quantum well asymmetry on the electroabsorption spectra of the system. As GaAs coupled quantum well structures are quite simple, which possess strong excitonic signals, these are being treated as the test systems for our study. Once this measurement is done, we will our results for modulation ratio for GaAs CQW as a guidance for studying more complex systems, such as InGaAs/GaAs CQW systems.

C. Ion-implanted Photo-MESFETS

Recently, experimental studies indicate that electrical properties of GaAs devices are very responsive to the light of the visible and infrared frequencies. These studies prompted us to theoretically address the technological importance of photo-MESFETs as high-speed photodetectors, optically switched amplifiers, and optical/microwave transformers. In order to address this, we have investigated the influence of optical illumination on the I-V characteristics of photo-MESFETs. We considered both long-channel and short-channel photo-MESFETs. For long-channel photo-MESFETs gradual channel approximation of Shockley was used to calculate the I-V characteristics. In the case of short-channel photo-MESFETs the saturation of electron velocity due to high electric field was taken into consideration, and a new approximation for field-dependent electron velocity developed in our earlier investigation was used to model the I-V characteristics. For this modeling, the distribution of optically generated carriers in the channel was represented by an exponential function. The distribution of doping-dependent carriers was, however, described by a Gaussian function. As we were interested in exploring the physical mechanism underlying the experimental behavior of photo-MESFETs, we took utmost care to analytically present our model. For this we approximated Gaussian function by a series of exponential functions, the latter being in quantitative agreement with the former over a range required by active device operation.

To our knowledge, the present phyical analysis of the I-V characteristics of photo-MESFETs carried out in detail represent one of the first successful attempts to determine the usefulness of photo-MESFETs as photodetector, photo-receiver, and/or optically switched amplifier. Our results suggest that in the case of both long-channel and short-channel photo-MESFETs a proper optimization of optical flux and of the wavelength of incident light should lead to the maximization of drain saturation current as well as transconductance. In the case of long-channel photo-MESFETs the effect of light should greatly enhance drain saturation current to about 300 mA/mm, and the transconductance to about 260 mS/mm. In the case of short channel photo-MESFETs (channel length=0.5 μm), the effect of optical illumination should enhance the drain saturation current to about 700 mA/mm, and the transconductance to about 700 mA/mm. Our results agreed well with experimental results on photo-MESFETs, lending strong support to the mechanism assumed to be responsible for the operation of photo-MESFETs. These mechanisms are as follows : (1) The light should be incident on the transparent or semitransparent gate region. (2) Due to absorption of light electron-hole pairs are generated just below the gate within the depletion region. (3) Free carriers generated by photon absorption participate in the conduction process in the same way as the free carriers due to donor ionization.

D. Crystal Growth by Gas Source Molecular Beam Epitaxy

Gas source Molecular Beam Epitaxy GSMBE is the newest development in epitaxial growth technology. It allows an advantage of clean growth environment with no memory effects. It produces crystals with hyper abrupt interfaces, extreme uniformity, and no flow pattern problems. It is easy to use for in-situ analysis of instruments such as RHEED and RGA. It allows selective growth of semiconductor crystals over SiO_2 patterned substrates. Our progress in the establishment of GSMBE facility, which is going to be the most important component of our research effort in optoelectronics is described as follows:

So far we have acquired all the components necessary for the Gas Source MBE system. We have obtained a fully dedicated gas delivery system from Precision-Flow Devices. We have been trying to determine if four gas purge panels of the GSMBE for Arsine, Phosphine, Germane and Silane respectively will work well. They should be state-of-the-art models employing standard safety features and compatibility with our custom-made gas manifold cabinet. We have worked to check if our custom designed gas manifold incorporates unique precision gas flow control system. It allows us to grow quaternary and ternary heterostructure device layers with great deal of compositional uniformity. We have worked also to check if the process gas flow in it can be controlled within 0.1 sccm. For this, we used a leak valve with a pressure transducer in the upstream for some of the gases, and mass flow controllers for the rest. This has been done because some of the gases have very low flow rates, while some others have high flow rates. The gas lines should be all coaxial tubing with the purge N_2 flowing through the shell. The purge gas will be continuously analysed by the multiple point toxic gas detector supplied by MDA Inc. We are examining if in the event of any problem the automatic purging will start, till the system returns to the safe status position. On the other hand, if the purge pressure increases, the process gas flow should be similarly discontinued till the normal conditions are once again established. The pumping system for the gas source MBE consists of a cryo-pump, a diffusion pump with three associated cold traps along with. We are fixing the system in such a way that the diffusion pump can be isolated from the rest of the line by using a gate valve, and the effluents from the pumps are vented through a coaxial tube to a scrubber which is also connected to the toxic leak detector. The effluents from the scrubber need to be non-toxic. We have a gas cracker as well as a solid cracker. The solid cracker incorporates some modifications so that it can produce a stabilized flux. We should be able to grow phosphorous based quaternary compounds. The gas cracker will be able to produce compositionally uniform fluxes for both arsenic and phosphorus, by utilizing its efficient cracking mechanisms for Arsine and Phosphine, respectively.

E. Multiple Quantum Well Laser

Multiple Quantum Well laser structures with $Ga_{0.47}In_{0.53}As$ wells separated by $Al_{0.48}In_{0.52}As$ or InP barriers will be grown on InP substrates. We are also in the process of trying to grow InGaAs/InP double heterostructure lasers on InP substrates. Our plan is to investigate if all of these lasers operate around the 1.5μm wavelength region, in which the optical fiber loss is minimum. We will grow and characterize GaInAsP/InP p-i-n photodiodes, most probably utilizing a conventional diffused InGaAs homojunction and a InP/InGaP/InP double heterojunction. They should be designed to have very low leakage currents. We shall also investigate $In_{0.53}Ga_{0.47}As$ photoconductive detectors on InP substrates. Our effort will center around trying to obtain high responsivity, high intensity dependent gains and detectivity of the detectors. The optimum operation wavelength for a detector is around 1.5μm. This wavelength appears to be compatible with that obtainable from GaAs/AlGaAs waveguides and InGaAsP lasers.

We will investigate GaAs/AlGaAs Multiple Quantum Well optical waveguide on InP substrates because of its advantages of low propagation losses. Gas Source MBE will be employed to produce high quality GaAs material on InP as in the case of electronic devices and lattice matched heterostructures and MQW's for optical device applications. The GSMBE will also enable us to grow phosphorus based semiconductor alloys on GaAs on Si. We shall employ InGaAs-GaAsP Strained Layer Superlattices for reducing threading dislocations due to the 4% lattice mismatch between GaAs and Si. This will enhance the quality of the epilayer. We shall be growing GaP on Si as an initial step towards growing other Phosphorus based semiconductors on Si using a GaAs buffer layer.

F. Heterojunction Bipolar Phototransistors

Recently we have undertaken a new project entitled, 'Theoretical and experimental studies of heterojunction bipolar phototransistors (HPTs)'.

The main purpose of the theoretical side of the study will be modelling the I-V characteristics and related properties of HPTs with different structures and anticipated properties. By means of studying different structures, the effects of device parameters such as doping modulation, compositional grading in the base and emitter regions and the introduction of intrinsic layers of various nature in the base-collector depletion region will be investigated. The material system chosen for these HPTs is the AlGaAs/GaAs system because it is well understood and established.

Experimental side of the study will be forwarded to support the therotical results on HPT performance. As a very first step, we are planning to investigate the effects of the position that the photogeneration takes place in the base region on the current gain. For this purpose we have grown novel structures. The fabrication of these phototransistors as HBT's have resulted in reasonable performances in terms of electrical properties. Namely, current gain varied from 20-250 for various structures. The fabrication techniques for the phototransistor operation are under investigation. Necessary measurements will be performed in our laboratory.

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$Al_{0.3}Ga_{0.7}As/GaAs$ metal-insulator-semiconductor-type field-effect transistor fabricated on an InP substrate

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A metal-insulator-semiconductor-type $Al_{0.3}Ga_{0.7}As/GaAs$ field-effect transistor with 1-μm-long by 145-μm-wide gates and intrinsic transconductance of 180 mS/mm has been demonstrated on an InP substrate. The dislocation propagation is minimized by incorporating a superlattice on InP, and a 1.5 μm undoped GaAs buffer layer is grown prior to the actual channel to ensure good quality of the 250 Å active layer. A channel mobility of 1920 $cm^2/(V\ s)$ and a carrier concentration of $1.28\times10^{18}\ cm^{-3}$ have been measured at 300 K. The device exhibits excellent pinch-off, and the gate-to-source reverse breakdown voltage is greater than 5 V. The low output conductance of 2.5 mS/mm indicated small parallel conduction in the undoped GaAs buffer layer. Also, very little hysteresis was found in the current-voltage characteristics, implying few traps in the epilayer.

AlGaAs/GaAs Single Heterojunction Bipolar Transistors Grown on InP by Molecular Beam Epitaxy

by

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ABSTRACT

AlGaAs/GaAs single heterojunction bipolar transistors grown on InP substrates by molecular beam epitaxy have been fabricated and tested. An eight period 25 Å /25 Å $In_{0.53}Ga_{0.47}As/GaAs$ strained layer superlattice is incorporated in the buffer structure to reduce dislocation propagation to the active region. Small-signal common emitter current gains of about 20 and 30 at a collector current density of 2 x 10^3 A/cm ^{2} have been obtained for devices on InP as compared to about 60 and 150 for those on GaAs in structures with base thickness of 0.12 μm doped with Be to 1 x 10^{19} and 1 x 10^{18}cm^{-3}, respectively. Current densities as high as 1 x 10^4 A/cm ^{2} have been achieved in these devices with emitter area of 50 x 50- μm^2 without degradation demonstrating the excellent stability of this material. From the collector current dependence of the current gain, ideality factors of 1.3 and 1.2 for the emitter junctions have been obtained for devices on InP and GaAs, respectively.

OPTICALLY CONTROLLED CURRENT-VOLTAGE CHARACTERISTICS OF ION-IMPLANTED MESFETs

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Abstract

Optically controlled MESFETs are useful as optical devices for optical communications, and as photodetectors. In this paper, a theoretical model for the I-V characteristics of these MESFETs is presented. The model considers the nonuniform Gaussian doping for ion-implanted channels. It takes both the photogenerated carriers as well as the doping generated residual carriers into account. It is noted that the density of photogenerated carriers in the channel due to diffusion is much less than that due to drift. Treatment both under gradual channel approximation and saturation velocity approximation has been presented. The gradual channel and the velocity saturation approximations are applied to study the I-V characteristics of long-channel and short-channel MESFETs, respectively. Results for both long-channel and short-channel MESFETs indicate that drain saturation current and transconductance can be improved by properly fixing the optical flux, and the absorption coefficient of the material.

Photoluminescence studies of GaAs grown on InP substrates by molecular beam epitaxy

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GaAs-based field-effect transistor structures have been grown on InP substrates with the InGaAs/GaAs strained-layer superlattices and 1.5 μm GaAs layer as the buffer. The low-temperature (4 K) photoluminescence (PL) from this GaAs buffer has been studied for the first time. Among five observable peaks, the excitonic transition at energy 1.513 eV and the impurity associated recombination at energy 1.483 eV have been identified with the aid of reflection, absorption, and temperature and excitation-intensity dependent PL measurements. The peak at 1.504 eV, most probably due to an exciton bound to a defect, is greatly enhanced compared with that of homoepitaxially grown GaAs. The optical results show that GaAs films of good quality can be grown on InP substrate, which is consistent with device results.

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